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ACOUSTOELASTIC EFFECT FOR RAYLEIGH SURFACE WAVES IN THE PRESENCE OF A NONUNIFORM STRESS FIELD

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The acoustoelastic effect for Rayleigh waves on the inner diameter of a right circular steel cylinder was investigated. The velocity dependence on stress was studied as a function of frequency. As expected, the change in velocity was proportional to the applied stress at the surface. As a result of the nonuniformity of the applied stress field, however, the proportionality constant was expected to depend on frequency. Such a frequency dependence was

(CONT'D ON REVERSE)

20. ABSTRACT (CONT'D)

cont'd → observed and interpreted in light of existing theoretical predictions for the velocity behavior of Rayleigh waves in the presence of a nonuniform stress field.

Keywords -

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INTRODUCTION

The change in velocity of an acoustic wave in a solid due to stress is known as the acoustoelastic effect. Hughes and Kelly (ref 1) as well as Bach and Askegaard (ref 2) have derived expressions for the velocities of plane acoustic waves in homogeneously stressed, isotropic, and homogeneous solids. These expressions show, to a first-order approximation, that the relative change in velocity ($\Delta v/v$) is proportional to the uniaxial stress or a linear combination of the triaxial principal stresses, with coefficients that are functions of the second- and third-order elastic constants. The calculations, unfortunately, are not readily extendable to Rayleigh waves or inhomogeneous stress situations.

Hayes and Rivlin (ref 3) calculated the acoustoelastic effect for Rayleigh waves propagating on the surface of a uniformly stressed material. These calculations were later extended by Hirao, Fukuoka, and Hori (ref 4) to one particular configuration of Rayleigh wave on an inhomogeneously stressed medium. Again, the calculations have the disadvantage that they are not directly applicable to situations involving other configurations of Rayleigh wave and inhomogeneous stress, including the one considered in this report.

The perturbation theory for acoustoelastic effects as recently developed by Husson and Kino (refs 5,6), however, is quite general and can be applied in a straightforward way to various configurations of acoustic waves and homogeneous or inhomogeneous stress states. We have applied this theory to the Rayleigh wave situation as encountered in our work.

References are listed at the end of this report.

THEORY

The starting point for applying this perturbation theory to Rayleigh waves is the corrected form of Eq. (20) from Reference 6:

$$\begin{aligned}\delta\phi = -\frac{\omega}{4P}\int_V \Big(\frac{\partial b_m}{\partial a_m}&\left\{(2\ell+\lambda)[A(a_2) + B(a_2) + C(a_2)] + (\lambda+m)D(a_2) + mE(a_2)\right\}\\ &+ \frac{\partial b_1}{\partial a_1}\left\{-(\lambda+2m-n)C(a_2) - \frac{n}{2}[D(a_2) + E(a_2)]\right\}\\ &+ \frac{\partial b_2}{\partial a_2}\left\{(2\lambda+6\mu+4m)A(a_2) + \mu[2D(a_2) + E(a_2)]\right\}\\ &+ \frac{\partial b_3}{\partial a_3}\left\{(2\lambda+6\mu+4m)B(a_2) + \mu[2D(a_2) + E(a_2)]\right\}\Big)dV \qquad (1)\end{aligned}$$

(Here and throughout the report we employ the Einstein summation convention.) In this equation, $\delta\phi$ is the phase shift experienced by the Rayleigh wave. $\partial b_m/\partial a_m$ are the derivatives of the static displacements (static strains). λ, μ, l, m, and n are the Lamé and Murnaghan constants (second- and third-order elastic constants). The a_i are the coordinate axes, with a_3 in the direction of propagation and a_2 normal to the surface and directed inward. ω is the angular frequency. P is the average power flow given by (ref 6):

$$P = \frac{\rho v_R}{2}\int_S \left(\left|\frac{\partial u_2}{\partial t}\right|^2 + \left|\frac{\partial u_3}{\partial t}\right|^2\right)dS \qquad (2)$$

where ρ is the density of the undeformed material, v_R is the Rayleigh wave velocity, and u_i are the particle displacements for the Rayleigh wave. A, B, C, D, and E are functions of a_2 as determined from the following:

$$A(a_2) = \left|\frac{\partial u_2}{\partial a_2}\right|^2 \quad , \quad B(a_2) = \left|\frac{\partial u_3}{\partial a_3}\right|^2$$

$$C(a_2) = 2\mathrm{Re}\left(\frac{\partial u_2}{\partial a_2}\frac{\partial u_3^*}{\partial a_3}\right) \quad , \quad D(a_2) = \left|\frac{\partial u_2}{\partial a_3}\right|^2 + \left|\frac{\partial u_3}{\partial a_2}\right|^2$$

$$E(a_2) = 2\mathrm{Re}\left(\frac{\partial u_2}{\partial a_3}\frac{\partial u_3^*}{\partial a_2}\right) \qquad (3)$$

The particle displacements u_i for a Rayleigh wave propagating along a_3 are given by (refs 6,7,8):

$$u_1 = 0$$

$$u_2 = Q \frac{\beta}{\omega} \left(e^{-\alpha_S a_2} - \frac{2\alpha_S \alpha_L}{\beta^2 + \alpha_S^2} e^{-\alpha_L a_2}\right) e^{-i(\beta a_3 - \omega t)}$$

$$u_3 = iQ \frac{\alpha_S}{\omega} \left(e^{-\alpha_S a_2} - \frac{2\beta^2}{\beta^2 + \alpha_S^2} e^{-\alpha_L a_2}\right) e^{-i(\beta a_3 - \omega t)} \tag{4}$$

where

$$\beta = \frac{\omega}{v_R} \quad , \quad \alpha_S = \left(\beta^2 + \frac{\omega^2}{v_S^2}\right)^{1/2} \quad , \quad \alpha_L = \left(\beta^2 + \frac{\omega^2}{v_L^2}\right)^{1/2} \tag{5}$$

The shear, longitudinal, and Rayleigh wave velocities (v_S, v_L, and v_R) are in turn given by (refs 7,8):

$$v_S = \sqrt{\frac{\mu}{\rho}} \quad , \quad v_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad , \quad v_R = \left(\frac{0.87 + 1.12\nu}{1 + \nu}\right) \tag{6}$$

with ν, Poisson's ratio, given by

$$\nu = \frac{\lambda}{2(\lambda + \mu)} \tag{7}$$

After evaluating the integrands in Eqs. (1) and (2) over a unit length along a_1, a length L along a_3, and from 0 to ∞ along a_2, we calculate the relative change in velocity, $\Delta v/v$, using (ref 6):

$$\frac{\Delta v}{v} = \frac{\partial b_3}{\partial a_3} - \frac{\delta \phi v_R}{\omega L} \tag{8}$$

Of course to perform the integrations, one needs to assume a form for the static strains consistent with a load applied as shown in Figure 1. We assume that the normal stresses σ_i vary linearly with depth a_2:

$$\sigma_1 = 0 \quad , \quad \sigma_2 = (H_2 a_2)\sigma_o \quad , \quad \sigma_3 = (1 + H_3 a_2)\sigma_o \tag{9}$$

where σ_o is the surface stress in the a_3 direction, and the constants H_2 and H_3 must be determined by applying the principles of elastic theory to the geometry of our specimen and load. Application of Hooke's law will then yield the static strains to use in Eq. (1).

The assumptions of Eq. (9) lead to

$$\frac{\Delta v}{v} = (\gamma_1 + \frac{\gamma_2 H_2}{\omega} + \frac{\gamma_3 H_3}{\omega})\sigma_o \tag{10}$$

where the γ_i are complicated functions of the second- and third-order elastic constants and the density. They are best evaluated numerically rather than analytically. The acoustoelastic constant for Rayleigh waves in this situation would then be equal to the term in parentheses.

CALCULATIONS

For the type of steel used in this study (ASTM A723/MIL-S-46119A), the elastic constants and density have been found by Scholz and Frankel (ref 9):

$$\lambda = 110.3 \text{ GPa}$$

$$\mu = 79.9 \text{ GPa}$$

$$l = -388 \text{ GPa}$$

$$m = -624 \text{ GPa}$$

$$n = -747 \text{ GPa}$$

$$\rho = 7.84 \text{ g/cm}^3$$

Using these values, we obtain $\gamma_1 = -0.00411$ 1/GPa, $\gamma_2 = -84.7$ m/(GPa-s), and $\gamma_3 = -79.7$ m/(GPa-s).

To determine H_2 and H_3, we first obtain the stresses in the ring as a function of radial position r using elastic theory (ref 10):

$$\sigma_2(r) = \frac{-F/D}{\ln(b/a) - \dfrac{b^2 - a^2}{b^2 + a^2}} \left[\frac{-a^2b^2}{(a^2+b^2)r^3} - \frac{r}{a^2 + b^2} + \frac{1}{r}\right]$$

$$+ \frac{2(a+b)F/D}{b^2 - a^2 - \dfrac{[2ab\ln(b/a)]^2}{b^2 - a^2}} \left[\frac{(b/a)^2\ln(r/b) - \ln(r/a) + (b/r)^2\ln(b/a)}{(b/a)^2 - 1}\right]$$

$$\sigma_3(r) = \frac{-F/D}{\ln(b/a) - \dfrac{b^2 - a^2}{b^2 + a^2}} \left[\frac{a^2b^2}{(a^2+b^2)r^3} - \frac{3r}{a^2 + b^2} + \frac{1}{r}\right]$$

$$+ \frac{2(a+b)F/D}{b^2 - a^2 - \dfrac{[2ab\ln(b/a)]^2}{b^2 - a^2}} \left[1 + \frac{(b/a)^2\ln(r/b) - \ln(r/a) - (b/r)^2\ln(b/a)}{(b/a)^2 - 1}\right] \quad (11)$$

F is the force compressing the ring at the split, D is the thickness of the ring in the axial direction, and a and b are the inner and outer radii, respectively. This solution is correct only in the region opposite the split. By dividing the derivatives of σ_2 and σ_3 by σ_3 at $r = a$, we obtain $H_2 = 12.42$ 1/m and $H_3 = -497.8$ 1/m (F and D drop out).

Using the above values of the γ's and H's in Eq. (10), we obtain

$$\frac{\Delta v}{v} = (B_o + \frac{B_1}{f})\sigma_o \quad (12)$$

where $B_o = -0.00411$ 1/GPa, $B_1 = 0.00615$ MHz/GPa, and f is the frequency in MHz. Figure 2 shows the theoretical acoustoelastic constant versus frequency.

EXPERIMENTAL METHODS

The specimen was a split ring of ASTM A723 steel (MIL-S-46119A) machined to the dimensions shown in Figure 1. An inhomogeneous stress was applied using a compressive load at the split. We used three longitudinal wave transducers mounted on plastic wedges cut to the critical angle to couple a longitudinal wave in the wedge to a Rayleigh wave on the surface. All three wedges were bonded to the steel with silicone rubber (GE RTV). The Rayleigh wave was introduced at the first wedge and received at the second and third ones.

Velocity data were taken using a computer-controlled measurement system (Matec Instruments, Model MBS-8000) based on phase detection methods developed by Peterson (ref 11). The block diagram of Figure 3 shows the system's main features. The measurement technique involves interactive automatic control of the frequency and measurement of phase relationships.

From the phase detectors shown in the figure, the computer receives signals proportional to the sine and cosine of each received pulse's phase with respect to the original reference wave. The computer can then calculate the amplitude and phase of each received pulse. Of necessity, the phase is calculated only as an angle between $-\pi$ and $+\pi$. Using an algorithm that interactively varies the frequency slightly and measures the corresponding phase shifts, the system calculates the transit time of the acoustic wave and the time difference between receipt of the pulse at the two receiving transducers. The system also calculates changes in that time difference, due to the application of various loads, by measuring the corresponding phase shifts.

For ease of discussion, let the transit time from the sending transducer to the first receiving transducer be T_1, and to the second receiving transducer, T_2. We then measured the time change $\Delta T = \Delta T_2 - \Delta T_1$ versus applied load. By measuring the strain on the outer surface of the ring (Figure 1) and using the principles of elastic theory (ref 10), we calculated the applied strain on the inner surface between the two receiving transducers. The relative change in velocity $\Delta v/v$ can then be calculated using

$$\frac{\Delta v}{v} = \epsilon_{ID} - \frac{\Delta T}{T_o}$$

where ϵ_{ID} is the strain at the inner diameter and $T_0 = T_2 - T_1$. The slope of $\Delta v/v$ versus surface stress, known as the acoustoelastic constant, is then obtained at various frequencies.

EXPERIMENTAL RESULTS

Figure 4 shows $\Delta v/v$ versus surface stress at 3 and 5 MHz. Figure 5 shows the experimentally obtained acoustoelastic constants for Rayleigh waves at frequencies between 3 and 5 MHz. A linear least squares fit of the acoustoelastic constants to Eq. (12) was then performed to obtain experimental values of the coefficients B_0 and B_1. We found that $B_0 = 0.009$ 1/GPa and $B_1 = -0.032$ MHz/GPa.

A number of explanations for the differences between the theoretical and experimental determinations of B_0 and B_1 are possible. One possible explanation is that the elastic constants used in the calculation are not representative of this sample. This specimen was cut from a cylinder that had previously undergone an autofrettage process (plastic deformation to induce compressive residual stress at the inner surface). Other treatments that the material was subjected to, such as cold rolling and forging, can also have drastic effects on the elastic properties of the material.

CONCLUSION

As expected, the relative change in Rayleigh wave velocity was observed to be proportional to the applied stress, with a proportionality constant known as the acoustoelastic constant, that varied with frequency. Furthermore, the variation of the acoustoelastic constant with frequency agreed crudely with the $B_0 + B_1/f$ form predicted by theory. The differences in magnitudes of B_0 and B_1 can possibly be attributed to changes in the elastic constants caused by treatments that the specimen had previously undergone.

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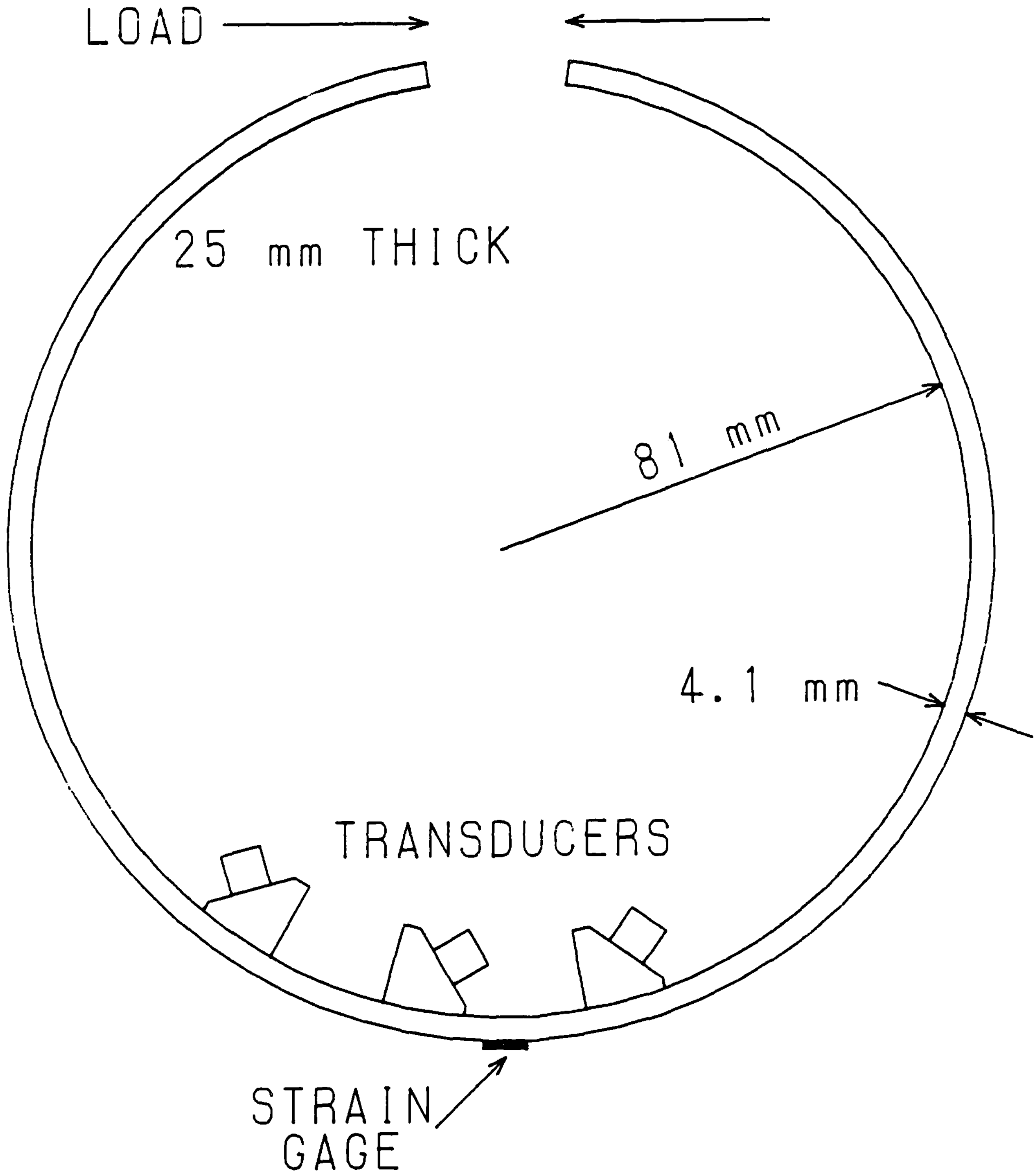

Figure 1. Sample and transducer arrangement.

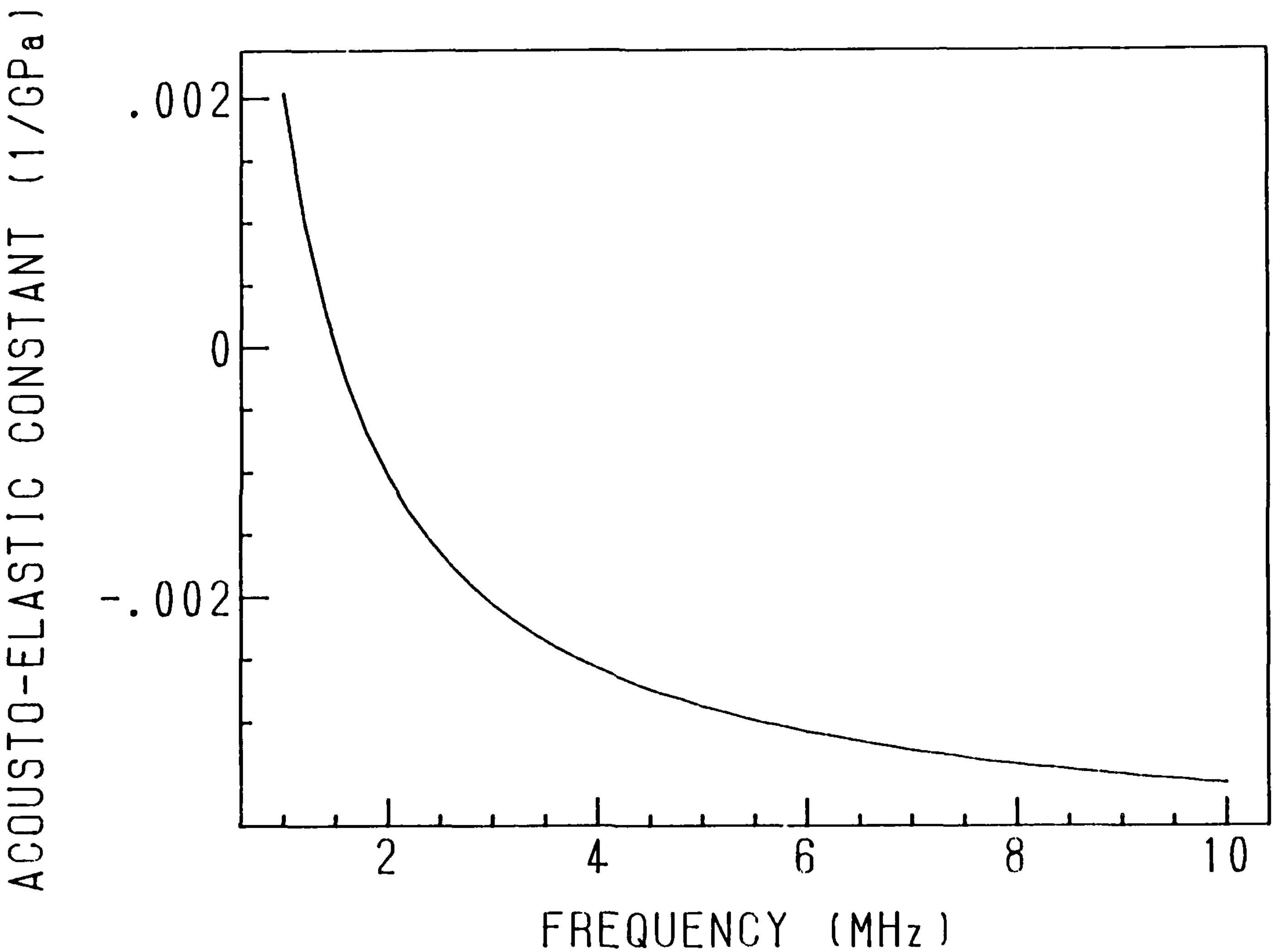

Figure 2. Theoretical acoustoelastic constant versus frequency.

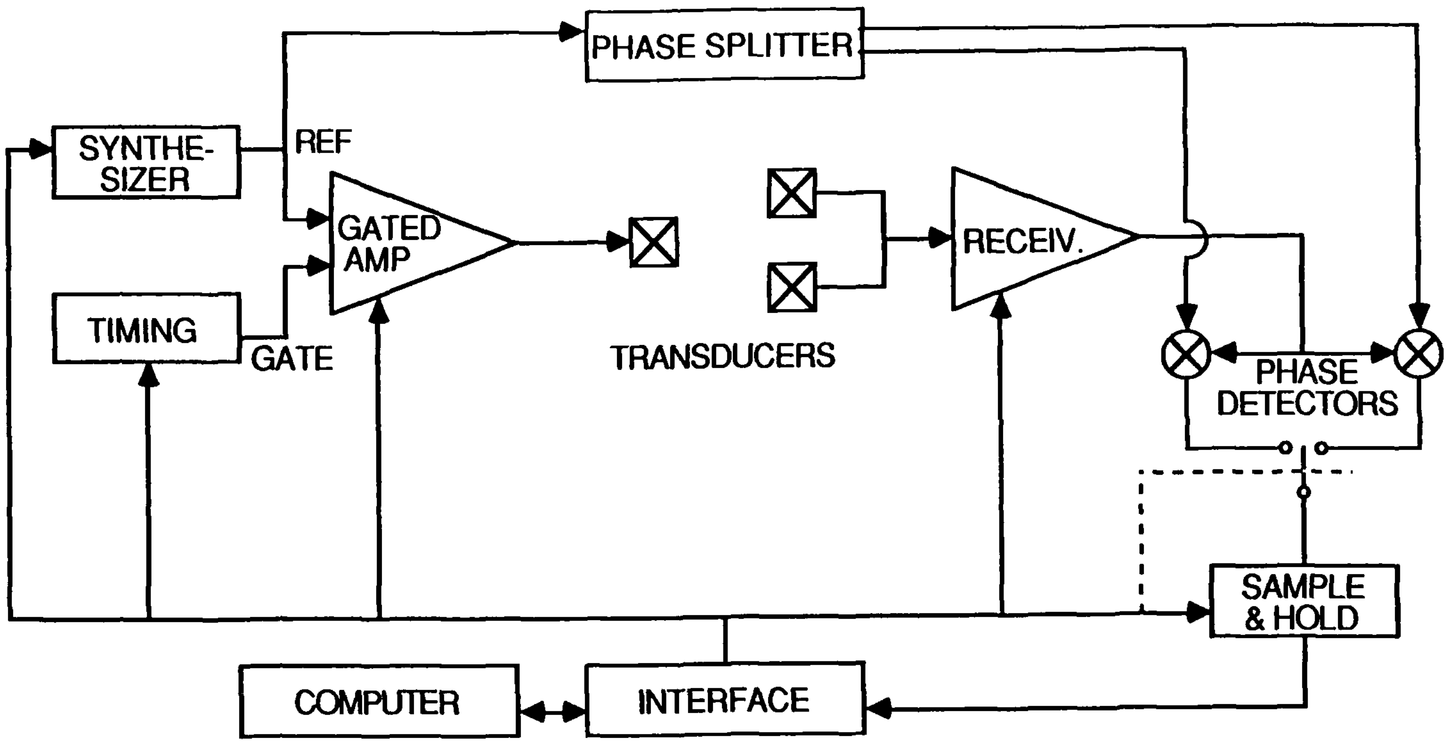

Figure 3. Computer-controlled ultrasonic velocity measurement system (Matec Instruments, Model MBS-8000) set up with one transmitting and two receiving transducers.

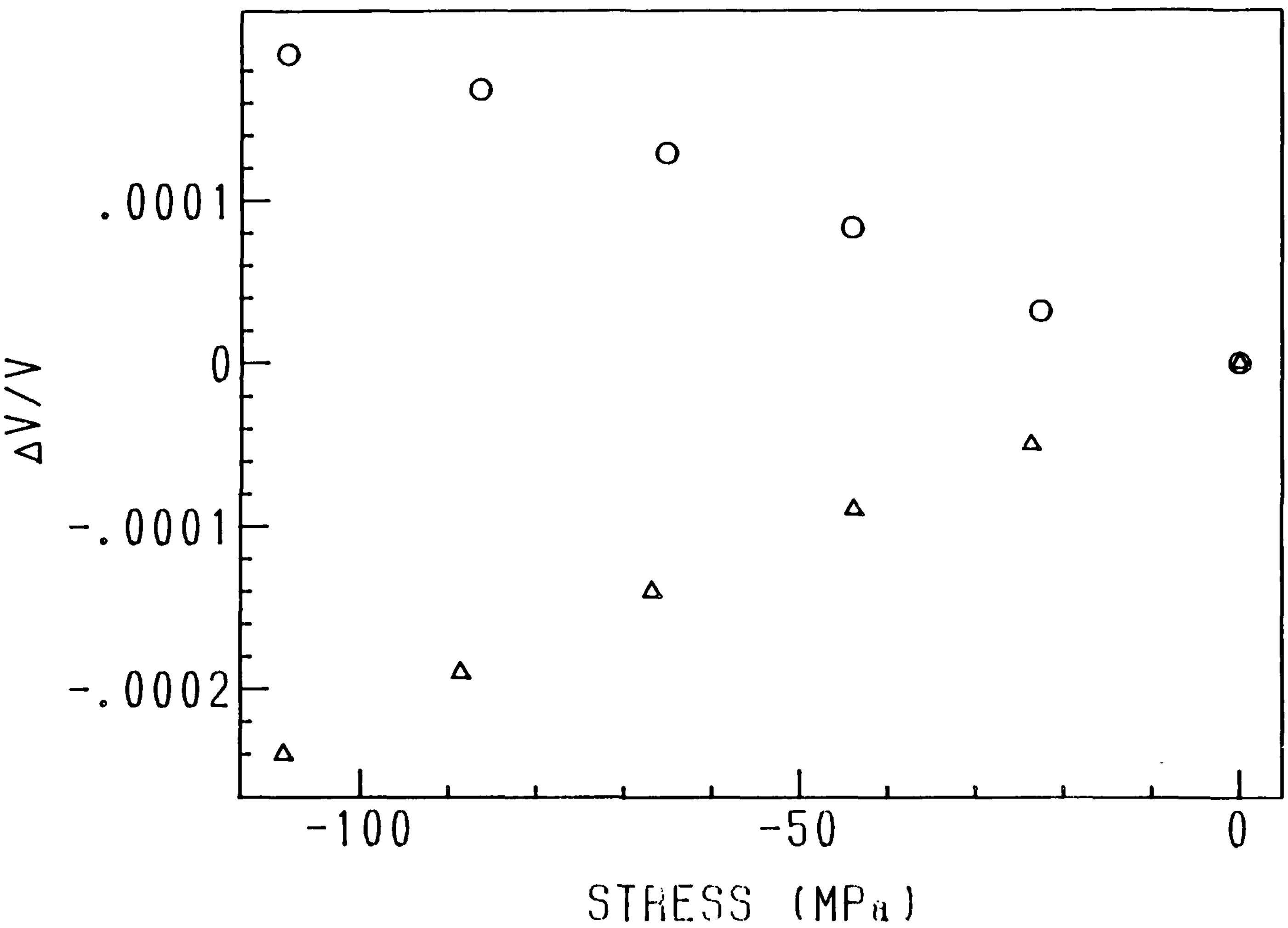

Figure 4. Δv/v versus surface stress at 3 MHz (circles) and 5 MHz (triangles).

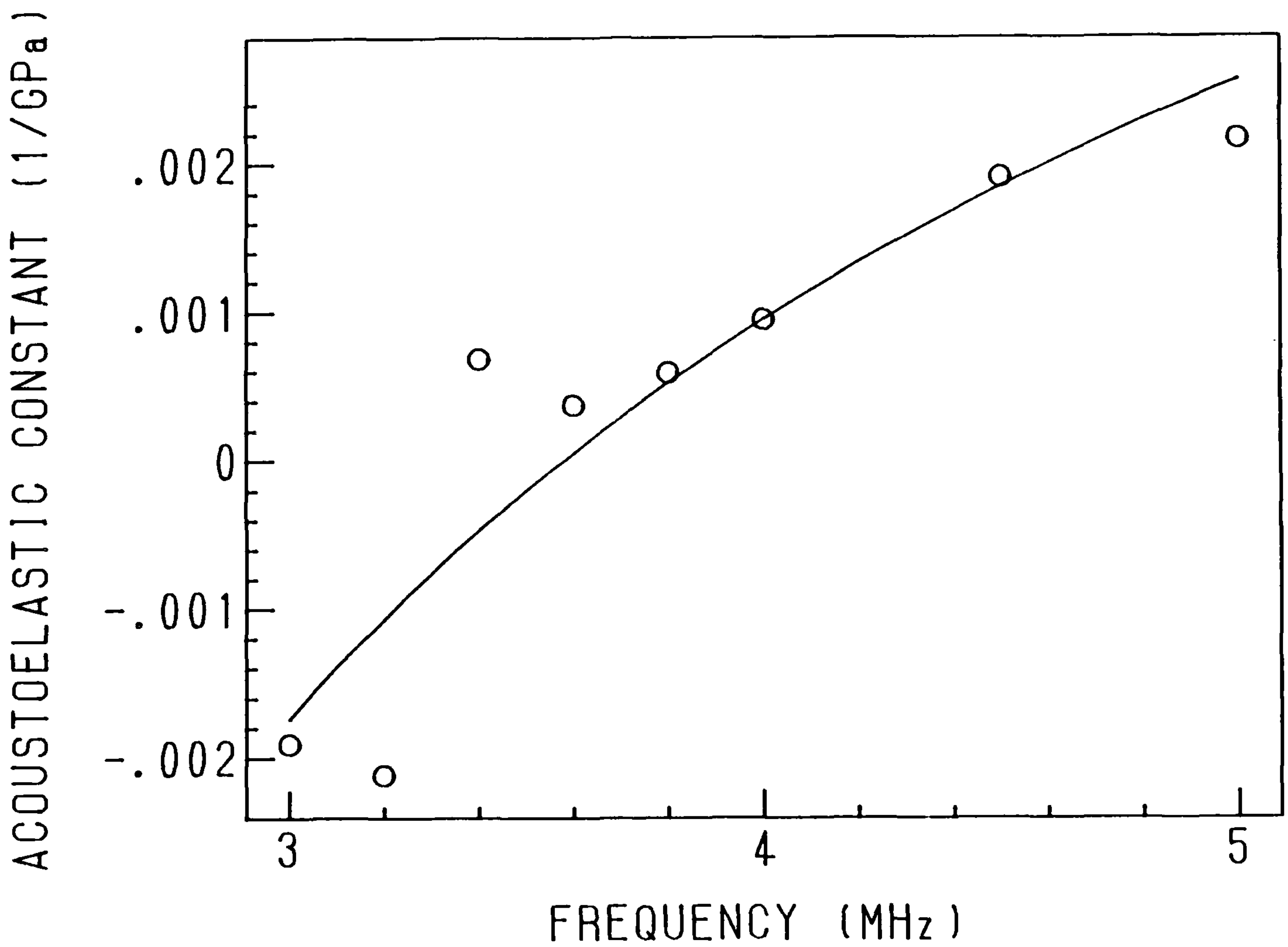

Figure 5. Experimental acoustoelastic constant versus frequency.

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